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Eric I. Thorsos

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FINAL REPORT: TRANSPORT THEORY FOR PROPAGATION AND REVERBERATION

by

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1. Background and scope of effort

The main goals proposed for this project were to extend transport theory to range dependent environments and to develop reverberation modeling based on transport theory. The stochastic process emphasized was forward scattering from the sea surface, since forward scattering from the sea surface has by far the most important effect on reverberation modeling that is not now being taken into account in reverberation modeling prediction for naval applications. As will be described in later sections, the effect of sea surface forward scattering can affect predicted reverberation levels at mid frequencies by more than 10 dB, and therefore it is one of very few physical effects (if not the only one) not presently being taken into account that can lead to such large reverberation modeling uncertainties.

The need to account for surface forward scattering with traditional reverberation modeling approaches readily accessable for naval applications is also being addressed. A separate project supported by PMW-120 (M. Speckhahn) has been ongoing with this particular goal in mind. The effect of surface forward scattering is treated with an effective surface reflection loss model for the total field (referred to as TOTLOS), where the total field is the combination of the coherent (or reflected) component, and the incoherent (or scattered) component. The original approach in developing TOTLOS was to base it on the results of Monte Carlo rough surface PE results, but as transport theory became available it became clear that results from it were much more suitable to support TOTLOS development. As a result TOTLOS development became an important secondary goal of the present project.

In following sections progress in extending transport theory to range dependent environments and to reverberation will be summarized. In addition, the approach being used with TOTLOS to provide similar capability to traditional codes based on ray, mode, or energy flux methods will be described, as well as how transport theory has been used in TOTLOS development. Before giving these results, however, some background will be given about the transport theory concept and the need for it in propagation and reverberaton modeling.

The subject of this project has been the development of an efficient and accurate method for modeling propagation and reverberation at low and mid frequencies in shallow water environments. In order for the method to be accurate at mid frequencies, an accurate treatment of forward scattering from rough boundaries is necessary. The need for such an accurate treatment can be understood qualitatively. In treating boundary forward scattering with ray-based methods, for example, the scattering process is highly simplified such that a loss is applied at each boundary interaction, which is otherwise treated as a reflection with the out-going grazing angle of each ray the same as its in-going grazing angle. This ignores the fact that forward scattering sprays the out-going energy over a range of grazing angles. And these effects accumulate with each boundary interaction, which means that this is a multiple scattering problem, a notoriously difficult problem to treat. Without accurately accounting for the change in propagating grazing angles, significant error does occur, for example, in reverberation prediction. This can happen because, except at very short ranges, the propagating field is composed mainly of components with low grazing angles. But at low grazing angles the backscattering strength, which determines the reverberation level, increases very rapidly with grazing angle. Therefore, the introduction of higher grazing angle components through forward scattering, though comprising a relatively small fraction of the total energy, can significantly impact the reverberation level.

The available options for modeling forward scattering in propagation are very limited, and are largely confined to computationally intensive methods that can yield benchmark solutions for certain simplified problems. When PE is used for practical propagation modeling, only large-scale bathymetry variations are included with small-scale boundary roughness ignored. Even the simple expedient of using a loss at the boundary to approximately account for boundary roughness is not conveniently included in PE propagation simulations. Similarly, normal mode methods generally ignore mode coupling due to boundary roughness in forward propagation, and in reverberation simulations only a single scattering (the backscattering) is included. In order to include the stochastic effects of boundary forward scattering, investigators have typically applied a full-wave method, such as PE, and performed propagation simulations using many realizations of the fluctuating environment in a “Monte Carlo” approach. Averaging the results over the set of realizations can then give accurate results for averages (or moments) of the field, and by using a sufficient number of realizations even pdfs of field amplitudes or intensities can be obtained. In the case of boundary roughness scattering, simulations using the finite element method have also been used. The computational demands for full-wave Monte Carlo simulations for propagation and particularly for reverberation are severe, and for reverberation these demands have limited such work to two-dimensional problems at low frequencies [1, 2].

Instead of doing time consuming Monte Carlo simulations, much faster solutions for field moments can be obtained if equations governing the evolution of the moments themselves can be obtained and solved. There is a long history in this approach for one-way propagation through internal waves. See, for example, the monograph by Uscinski [3]. Any method that works with evolution equations for the moments of the propagating quantities can be described as a “transport theory,” though not always referred to as such. While transport methods have been applied to propagation through internal waves, there has been little work on extension to propagation in the presence of rough boundaries or to reverberation (except for work by our APL-UW group). The historical emphasis on internal waves may be due to their importance even at low frequencies where boundary scattering is less important. For mid frequencies forward scattering from both internal waves and boundary roughness are of importance.

Therefore, the need has existed for much faster computational approaches for obtaining moments of the field for propagation and reverberation at mid frequencies that can account for rough boundary scattering. Our approach is based on expanding the acoustic field in modes, and therefore would most readily apply at mid-frequencies and below, and in relatively shallow water environments such as on the continental shelf.

Comparisons with rough surface PE simulations [4] are used to verify the accuracy of the transport theory method for the case of one-way propagation.

2. Transport theory for range dependent environments

Previous work had assumed a range independent environment, aside from the rough sea surface. And, a range independent environment is particularly convenient with a mode-based approach, since then all mode coupling arise from rough sea surface scattering, and not from propagation itself in the absence of the rough sea surface. For practical applications, however, it would be important to account for larger-scale range dependence of the environment. Thus, we have generalized our transport theory method to account for slowly varying range dependence in the bottom depth. For a slowly varying depth, we can expect that the adiabatic mode approximation would be useful. Therefore, the accuracy of the adiabatic approximation was first examined for the case of a linear depth change with range. In particular, the depth was varied linearly from 50 m at the start to 45 m at range R_0. To examine the adiabatic approximation, PE runs were made with a flat sea surface and the linearly varying bottom depth at a frequency of 3 kHz. Mode projections of the PE fields (using range varying mode sets) show little mode coupling unless R_0 is reduced to about 1 km. For R_0 several times greater than 1 km, the adiabatic approximation is found to be very good, i.e., there is very little mode coupling. Therefore, transport theory has been modified to use adiabatic modes with linear interpolation between several mode sets with different bottom depths to account for changes in mode horizontal wave numbers and in the mode functions. Even for $R_0 = 1$ km, the mode coupling is only significant to nearest neighbor modes. Therefore, to go beyond the adiabatic approximation in future work, it may be sufficient in many cases to only consider nearest-neighbor mode coupling.

The problem considered is CW propagation at 3 kHz in two space dimensions with a source at mid depth. A rough sea surface is described by a 1-D Pierson-Moskowitz roughness spectrum for a wind speed of 7.7 m/s (15 knots). The waveguide depth varies linearly from 50 m to 45 m at a range of 12 km in the first example. The sea floor sediment has sound attenuation of 0.5 dB/wavelength. The sound speeds are 1500 m/s in the water and 1600 m/s in the sediment. The computational region extends 50 m into the sediment, and continuum modes are represented as closely spaced discrete modes. For a 50 m depth there are 70 trapped modes, but 114 modes have been used to display the field penetrating into the sediment above the critical angle.

The penetrating field is mainly made up of modes with higher mode numbers than the "trapped modes," and sea surface forward scattering excites these higher modes, leading to continual loss into the bottom. For this set of "non-trapped modes," the mode structure in complicated, with "promoted modes" or true modes interspered with continuous modes, and the imaginary parts of the horizontal wave numbers differ dramatically between to two types of modes. Because of this, straighforward linear interpolation between mode sets with different bottom depths was not appropriate. It was also found that the continuous modes were not excited either by the original source or by forward scattering at the sea surface, and could effectively be ignored. Therefore, the first 200 modes were first reordered based on the imaginary parts of the horizontal wave number, effectively excluding the continuous modes, leaving a total of 114 modes, and then interpolations between mode sets at difference bottom depths could be used to account for the range dependence of the adiabatic modes.

For the transport theory results, the Dozier-Tappert approximation (see [5]) has been made. This is a neglect of cross-mode coherences in the incoherent intensity. Comparisons with the rough surface PE simulations have shown that there is very little loss in accuracy in making this approximation.

Figure 1 shows a comparison between PE and transport theory results for the total intensity that includes the coherent intensity plus the forward scattered intensity. The propagated total intensity can be represented as $\langle|p|^2\rangle$, where $\langle\ \rangle$ denotes an average over an ensemble of rough sea surface realizations. For the transport theory result (bottom panel), the averaging has been formally done. For the rough surface PE simulation result (top panel), the averaging has been done numerically using the results for 50 surface realizations. Note the change in depth from 50 m at the start to 45 m at 12 km range. The periodic focus points at mid depth are shifted to slightly shorter ranges than for a constant depth of 50 m. In particular the constant depth focus at a 10 km range has been shifted to a range of about 9.3 km. The adiabatic mode result matches fairly well the focus locations and other detailed features of the PE result, including the field that is shown penetrating into the sediment, which occurs mainly due to forward scattering from the sea surface.

It should be kept in mind that transport theory is much faster than full wave approaches that use a Monte Carlo method with many rough surface realizations. Also, any number of forward scattering interactions can be accounted for as the field propagates along the waveguide. Even though transport theory is relatively fast, it still may not be realistic to expect that present simulation methods based on rays, modes, or energy flux in naval applications would make a transition to transport theory in the near future in order to account for effects of boundary roughness on shallow water propagation and reverberation. This is a strong motivation for the TOTLOS model development (Section 4) since that model can be used with traditional simulation methods, which also can readily account for large-scale range dependence. The important of generalizing transport theory to incude range dependence, then, is to provide tests of TOTLOS predictions for reverberation in range dependent environments, not as easlily done with PE or other full-wave methods.

3. Transport theory for reverberation

Transport theory has been extended from one-way propagation scenarios to full reverberation modeling, and important effects of surface forward scattering are included. The reverberation can be due to scattering from the sea surface, the sea floor, or both, but at this stage forward scattering during propagation out and back from a given scattering patch is due only to the rough sea surface. For most environments and at mid frequencies sea surface forward scattering will be much more important to include for reverberation modeling than bottom forward scattering. Reciprocity is used to relate the transmission amplitude from the source to a given scattering patch on the surface or bottom to the corresponding transmission amplitude on the return path. [The transmission loss in dB is −20 log (transmission amplitude).] For bistatic reverberation, transport theory is used in model forward propagation twice, one from the source position and one from the receiver position. For monostatic reverberation, only a single forward propagation run is required. Scattering theory based on perturbation theory is used to couple forward-going mode amplitudes to backward-going mode amplitudes at a given scattering patch. Surface forward scattering turns out to have very important effects on reverberation level at mid frequencies.

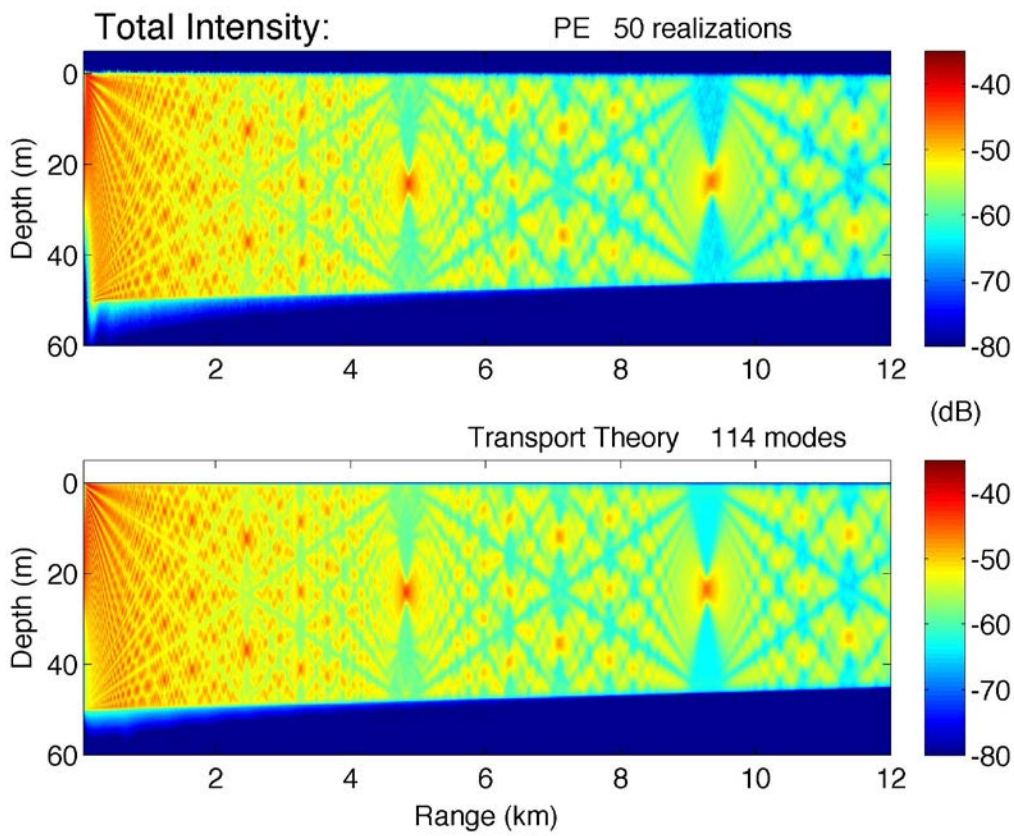

Figure 1. The total intensity for PE averaged over 50 surface realizations (top), and for transport theory (bottom) for a range dependent bottom depth and with a rough sea surface.

For the reverberation example presented the frequency is 3 kHz, the rough sea surface is modeled with an isotropic Pierson-Moskowitz roughness spectrum, the bottom is taken to have the Reverberation Modeling Workshop “typical roughness” model [6], the sound speed in the water is 1500 m/s, the sound speed in the sediment is 1600 m/s, the density ratio (sediment/water) is 2, and the attenuation in the sediment is 0.5 dB/λ. The water depth is 50 m, and another 50 m of sediment is included in the computation domain with the result that continuous modes are represents as closely spaced discrete modes. A 3-D geometry is assumed using the usual "N×2D model" where azimuthal divergence is included, but all propagation and scattering is confined to the 2-D vertical-range plane. A point source and point receiver are co-located at a water depth of 25 m. Incoherent mode superposition is used for the propagation out and back. This yields smooth reverberation curves for simplicity, but coherent superposition could just as well be used for the first moment contribution to yield the complicated waveguide propagation structure.

Figure 2 shows two sets of reverberation curves out to a time of 60 s, the lower set of three curves is for surface reverberation only, and the upper set is for surface and bottom reverberation. For the lower set the bottom is taken as flat with no roughness. For this example the wind speed is 7.7 m/s (15 knots) giving an rms wave height of 0.31 m, and a significant wave height of 1.3 m or about 4.2 ft. The source waveform was taken to be a Gaussian modulated CW with a pulse length determined by a 3 dB-down bandwidth of 3 kHz/20, or 150 Hz. The maximum amplitude at the peak of the pulse (at pulse center) is 1 μPa at 1 m. To obtain the equivalent reverberation level for a rectangular pulse with source level of 0 dB re 1 μPa at 1 m with a pulse length of 1/(150 Hz), one should add 6.29 dB to the curves shown.

Consider the surface reverberation curves first. When forward scattering is ignored (red curve) the reverberation prediction is too high because the effect of sea surface roughness in scattering energy out of the waveguide is being ignored. Thus, the effect of enhanced mode stripping due to scattering is not being taken into account. The solid green curve is the transport theory result based on the first moment of the field, and is equivalent to assuming a coherent scattering loss at the sea surface. This result is too low compared to the blue curve that includes surface forward scattering. The effect of forward scattering is to enhance the reverberation level (up to 20 dB in this case) over that given using a coherent loss model. Physically, this occurs because forward scattering is dominated by scattering relatively close to the specular direction. Therefore, while this scattering can result in energy being scattering above the critical angle (about 20 deg in this case) and then lost into the bottom, this mainly occurs through repeated scattering that in a random walk type of process eventually leads to scattered energy being removed from the waveguide. But it also leads to a significant residence time of this energy, as it is being repeatedly re-scattered while it has relatively high grazing angles, significantly increasing the reverberation level.

In many cases bottom reverberation dominates over surface reverberation, as shown by the upper set of curves, even for this isovelocity sound speed profile. However, the effect of surface forward scattering is still very important in modeling the reverberation correctly, since it enhances the higher grazing angle energy incident on the bottom. Neither option of ignoring effects of surface forward scattering (red curve) or using a coherent loss for the surface interaction (green curve) comes close to the result obtained by modeling the effect of surface forward scattering in detail (blue curve). These reverberation results have not been obtained before, and clearly show the importance of detailed modeling of surface forward scattering at mid frequencies on reverberation modeling. For these results forward scattering from roughness on the bottom has not been modeled, but under most conditions it can be expected to be significantly less important that surface forward scattering. Treatment of bottom forward scattering with transport theory is a topic of future work.

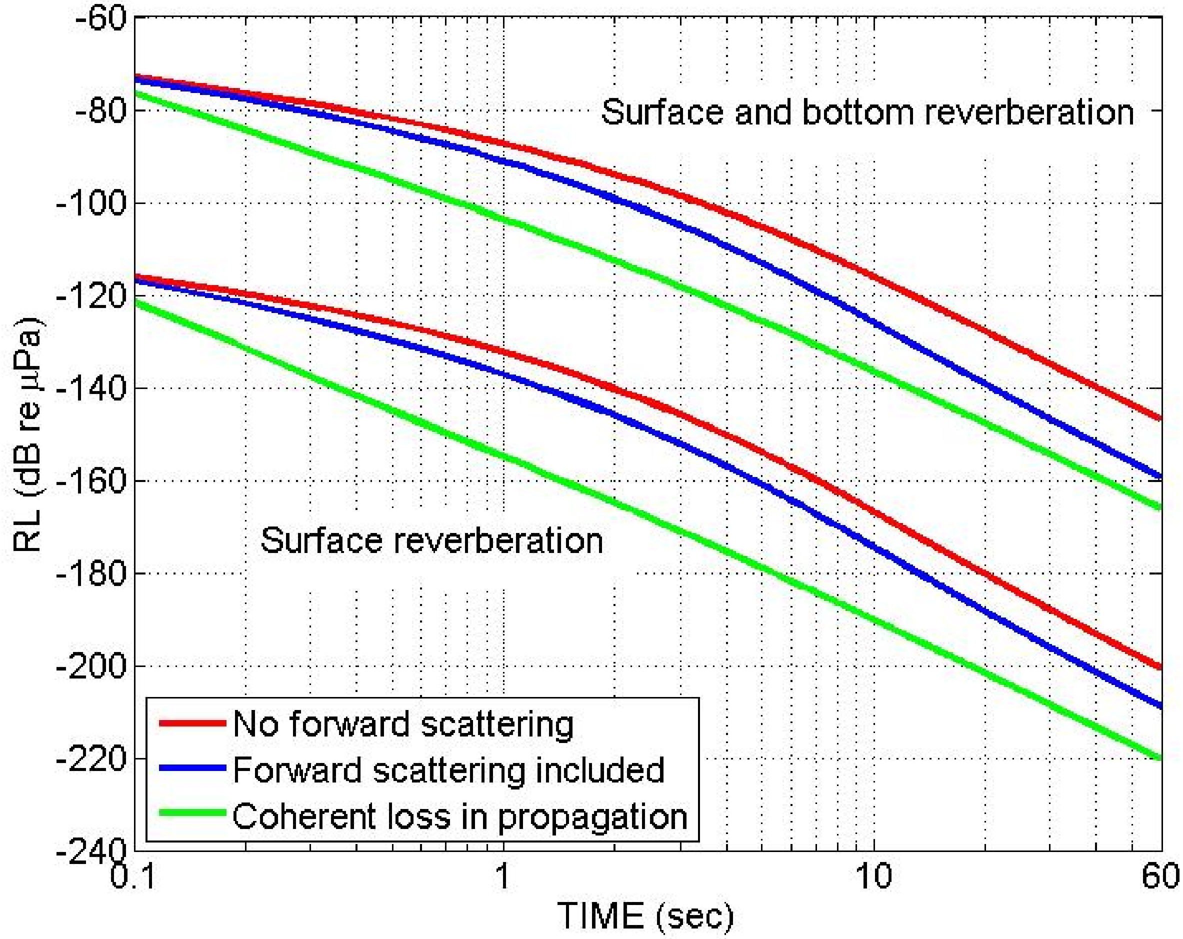

Figure 2. Reverberation predictions obtained with transport theory. The red curves ignore all effects of boundary roughness during propagation. The blue curves account for surface forward scattering. The green curves approximate the effect of surface forward scattering in terms of a coherent loss.

Making data/model comparisons to verify the important effects of forward scattering on mid frequency reverberation levels predicted by transport theory is made difficult by the need for comprehensive environmental characterization of the measurement site, not usually available. Indeed, that need was an important motivation for the basic research reverberation experiment (TREX13) carried out during the spring of 2013 near Panama City, Florida. However, the predicted effects are so great that some verification should be possible from previously existing data sets, though without detailed knowledge of the bottom backscattering strength corresponding to a reverberation data set there can be large modeling uncertainties.

Fortunately, a reverberation data set obtained during ASIAEX in 2001 [7] happens to have properties that allows a test of transport theory predictions while being insensitive to many of the usual modeling uncertainties. Figure 3 is taken from Fig. 9 in [7] and shows the measured normalized reverberation level (NRL) at 2 kHz (left) and 1 kHz (right) on June 3 and June 5, 2001. The normalized reverberation level was obtained by dividing the received level by the energy in the transmitted pulse at 1 m from the source. On June 3 the sea state was relatively low, while on June 5 the wind had increased leading to a higher sea state and a lower reverberation level. Modeling discussed in [7] indicates that bottom reverberation was dominant, and therefore the reduction in reverberation level at the higher sea state was undoubtedly due to the effect of forward scattering from the sea surface. Modeling the normalized reverberation level, even for a very low sea state, would require an accurate model for the bottom backscattering strength. However, for a change in reverberation level as the sea state changes, the sensitivity to the bottom backscattering level, as well as to most other environmenal descriptors, would be largely be removed. The change in reverberation level, shown in the lower panels in Fig. 3, should therefore be able to provide some verification of the accuracy of transport theory for modeling surface forward scattering effects.

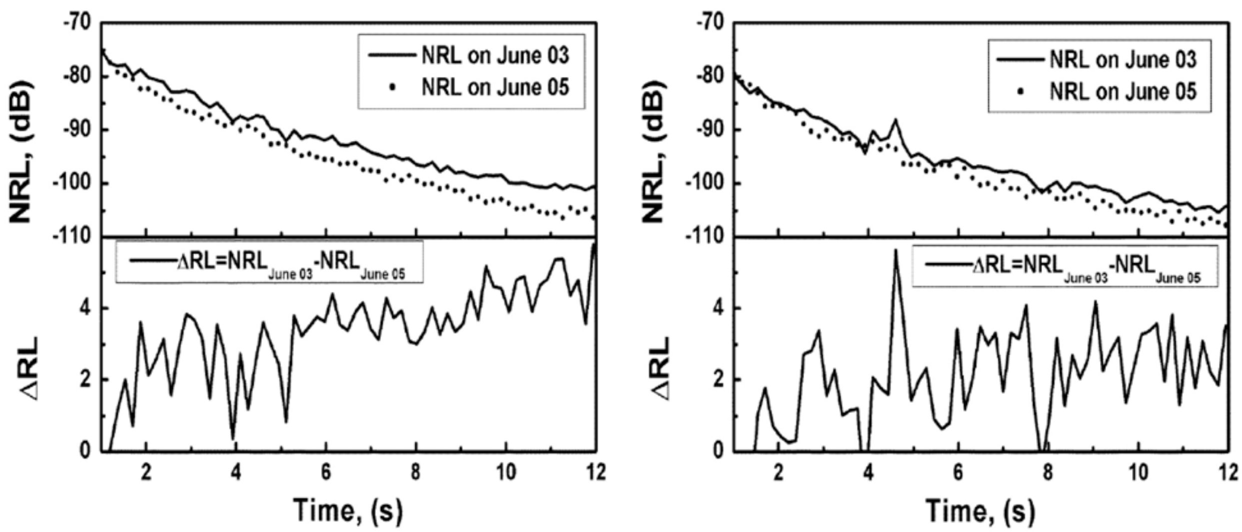

Figure 3. Normalized reverberation levels (NRL) at 2 kHz (left) and 1 kHz (right) measured during ASIAEX [7] at the same site on two different days. The higher sea state on June 5, 2001 led to lower reverberation levels, which were known to be dominated by bottom reverberation.

Because reverberation difference will be less sensitive to the environmental details, approximations can be made when modeling the lower panels in Fig. 3. On June 3 the wind speed is reported [7] as 3 m/s with an rms wave height of 0.1 m, and on June 5 the wind speed is reported as 9 m/s with an rms wave height of 0.35 m. Because both the explosive source and single hydrophone receiver can be considered a point source or receiver, the contributions to reverberation arise from a circular annulus, and directional aspects of the wave field will not be very significant. Thus, the surface roughness is modeled with the same isotropic Pierson-Moskowitz model used for Fig. 2 with the wind speed chosen to yield the reported wave heights. With this choice, the wind speed used for June 3 is 4.33 m/s and for June 5 is 8.10 m/s. The sound speed profile (Fig. 2 in [7]) was not perfectly isovelocity, but is approximated as isovelocity for the purpose of this comparison. The source and receiver depths are given in [7] as 50 m and 90 m, respectively. Bathymetry data at the site [8] indicate that use of an average water depth of 110 m is a reasonable approximation. The values for water and sediment sound speed, and sediment density and attenuation are as described in [7].

The measured reverberation differences [9] are compared with transport theory results in Figs. 4 and 5 for a frequency of 1 kHz and 2 kHz, respectively. If effects of surface forward scattering were ignored completely, corresponding to the red curves in Fig. 2, the differences in Figs. 4 and 5 would be 0 dB for all times (not plotted). If surface forward scattering were treated using the coherent reflection loss, corresponding to the green curves in Fig. 2 (using the first moment with transport theory), the predicted reverberation difference is given by the green curves in Figs. 4 and 5, showing greater differences than observed between the two sea state conditions. Finally, if surface forward scattering were treated in detail with transport theory (using the second moment with transport theory), the result is given by the blue curves, in remarkably good agreement with the data.

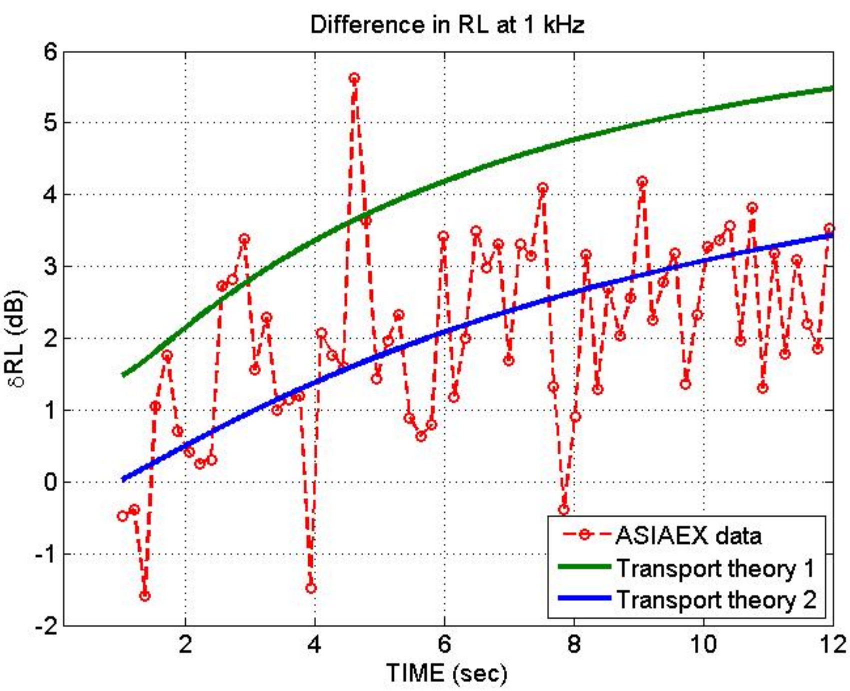

Figure 4. Data/model comparison for reverberation difference between June 3 and 5, 2001. The green curve assumes a coherent loss at the surface, while the blue curve accounts for forward scattering.

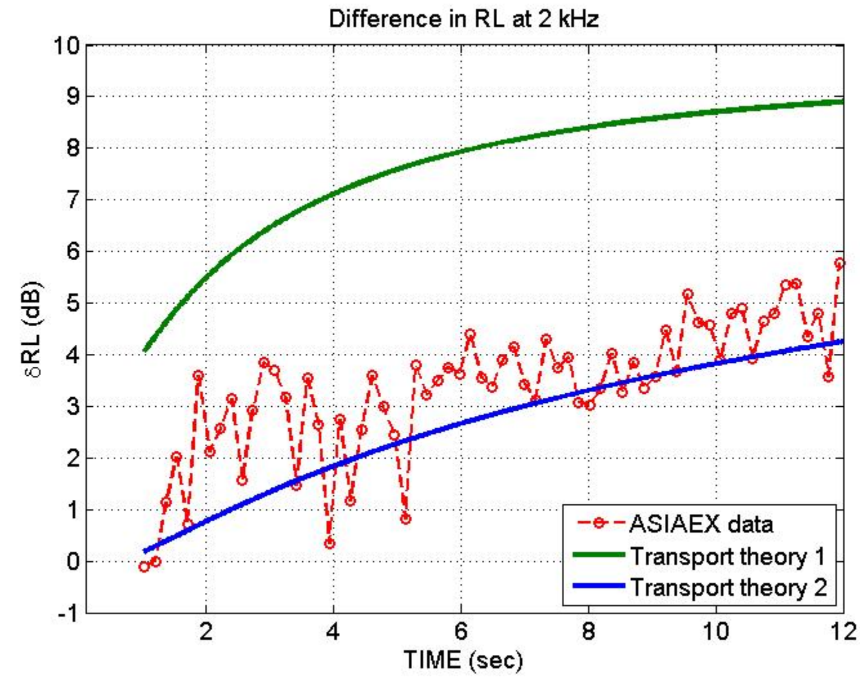

Figure 5. Same as Fig. 4 but for 2 kHz.

If must be appreciated that the transport theory results shown in Figs. 4 and 5 are completely constrained by the environmental conditions, the geometry, and the reasonable simplifying assumptions made. There were no degrees of freedom available to improve the agreement. This data/model comparison supplies a very satisfactory verification of the important effects of forward scattering in the mid frequency region for these relatively modest sea conditions at 1 and 2 kHz. Figure 2 indicates that at 3 kHz the magnitude of these effects is significantly greater. One goal for TREX13 was to obtain data sets for verification of these effects up to 3 kHz using absolute level comparisons, that is, not utilizing reverberation differences to reduce sensitivity to environmental conditions.

4. TOTLOS development

Because transports theory has shown the importance of accounting for sea surface forward scattering in accurately modeling shallow water reverberation at mid frequencies, it becomes imperative to develop as approximate way to include these effects into traditional ray-based or mode-based reverberation codes. As mentioned in Section 1, a separate project supported by PMW-120 (M. Speckhahn) has been ongoing with this particular goal in mind. The effect of surface forward scattering is treated with an effective surface reflection loss model for the total field (referred to as TOTLOS), where the total field is the combination of the coherent (or reflected) component, and the incoherent (or scattered) component. The original approach in developing TOTLOS was to base it on the results of Monte Carlo rough surface PE results for one-way propagation, but as transport theory became available for reverberation, it became clear that results from it were much more suitable to support TOTLOS development because reverberation level is affected to a much greater degree than one-way propagation loss. As a result TOTLOS development became an important secondary goal of the present project.

The approach being used in the development of TOTLOS will be summarized briefly. Because our transport theory is mode-based, it readily provides mode amplitudes as a function of range for any particular shallow water environment of interest. Each mode amplitude can be associated with a particular grazing angle at the sea surface. The decay of each mode amplitude over a cycle distance (the distance between surface interactions assuming reflected rays) is first determined, and the contribution of loss at the bottom is removed. What remains is identified as a loss in a single surface interaction, and in many cases that loss is negative, which means that there is a gain. In such a case more energy is being forward scattered into a particular mode than is being lost into the bottom in one cycle distance. With this information determined as a function of range for each mode, it is possible to form an effective reflection loss (the TOTLOS model) that will replicate the transport theory results for propagation when surface forward scattering occurs. The model can then be tested in reverberation geometries using TOTLOS in a ray-based code such as CASS-GRAB and making comparisons with transport theory reverberation results.

The TOTLOS model depends not only on the sea surface roughness and frequency, but on range and on the water column and bottom properties, i.e., the TOTLOS model is scenario dependent. To avoid the need to tune the model to each scenario with appropriate transport runs, the approach is to develop an algorithm using quasi-analytic expressions for the model parameters based on a selection of transport runs, and then use that algorithm to define the parameters for the model in general

An example of mode amplitude decays with range obtained using transport theory is shown in Fig. 6. For this example the sea surface is rough corresponding to a fully developed sea for a wind speed of 15 knots (7.7 m/s), the water depth is 50 m, the sound speed in the water is 1500 m/s (uniform in depth), the sound speed in the sediment is 1600 m/s, and the attenuation in the sediment is 0.5 dB/λ. In Fig. 6 the blue line at the top gives the amplitude for mode 1, which corresponds to a very low grazing angle. The amplitude for mode 2 is the next line down (green) and so on up to mode 70, with the grazing angle increasing with mode number. Mode 70 is the last trapped mode and its grazing angle is just below the critical grazing angle, about 20 degrees for this case. The idea behind the TOTLOS model is to adjust the surface reflection coefficient as a function of grazing angle and range to effectively reproduce the equivalent grazing angle dependent intensity decay with range when the model is used in a ray based code such as CASS-GRAB.

Note that in Fig. 6 the mode decays are divided into two quite distinct regions. In the upper portion of the figure the mode amplitudes decay nearly linearly with range on this log-linear plot, indicating that these low modes decay exponentially with range. Below that region there is a dividing line where many mode amplitudes are concentrated, and below that the mode spacing in amplitude is much reduced and the amplitudes decay more slowly with range. The dividing line occurs at the point where scattering (based on first-order perturbation theory) from a wave spectral component at the peak of the spectrum carries energy from the lowest mode to that dividing line boundary. Thus, the mode decay pattern clearly shows the important effect of forward scattering on the mode amplitudes. If no forward scattering were to occur (say, the surface was calm), the mode decays would all be similar to the region at the top, but with increasing decay rates as the mode number (and grazing angle at the bottom) increased.

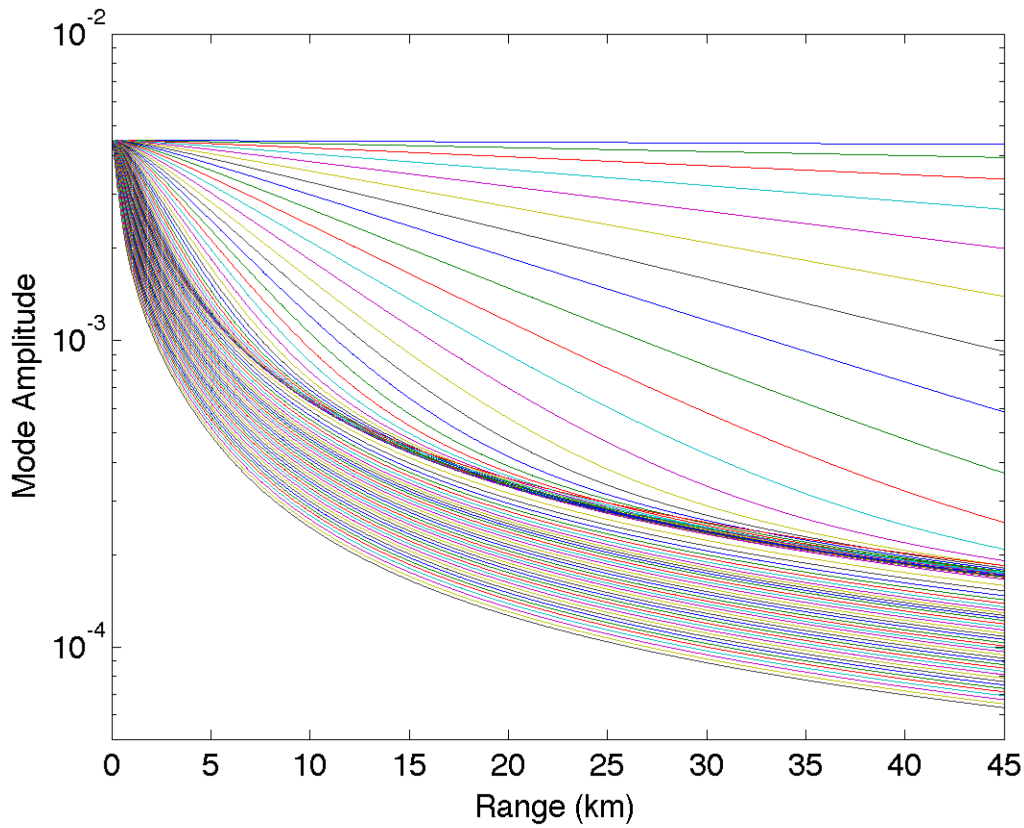

Figure 6. Mode amplitudes versus range for a wind speed of 15 knots, a frequency of 3 kHz, and a water depth of 50 m. A total of 70 mode amplitudes are included, starting from mode 1 at the top. These are the trapped modes for this case.

The mode amplitudes decrease with range in Fig. 6 in part because of scattering at the sea surface, but also because of mode attenuation due to absorption in the bottom. In a run with CASS-GRAB the losses in the bottom will occur though the bottom reflection coefficient. Therefore, the TOTLOS model is actually determined to effectively reproduce the mode amplitude dependence on range after the effects of the bottom losses have been removed, because these losses will be added back in by CASS-GRAB. When the effects of bottom losses are removed from the mode amplitudes shown in Fig. 6, they no longer monotonically decrease with range. The higher mode amplitudes near the bottom of the figure will now increase with range except at the shortest ranges. This effect arises because surface roughness can cause low grazing angle energy (in low modes) to scatter into higher grazing angle energy (in higher modes), and this redistribution in angle is being properly modeled with transport theory. This effect shows up in Fig. 6 in the higher mode amplitudes that start out decreasing rapidly with range but at longer range decrease much more slowly as their amplitudes are being replenished by the effects of surface scattering. The net effect of this process is that for TOTLOS the effective reflection coefficient at the surface for higher grazing angles will generally exceed unity to account for the effects of scattering from low grazing angles to higher grazing angles.

An effective reflection coefficient for the sea surface as a function of range and grazing angle can be deduced from the decay curves of the mode amplitudes shown in Fig. 6, after subtracting out the effects of loss at the bottom. Doing this would yield an effective reflection coefficient for the particular set of parameters that were used in the transport run, and could certainly be used in CASS-GRAB in a reverberation simulation for that case. However, that approach would not yield a satisfactory model for TOTLOS, because it could not be directly applied to cases with other parameters without first running the transport code for that new set of parameters. The critical step in developing the TOTLOS model is to use a modest number of transport runs over a range of environmental parameters to deduce a relatively simple algorithm that will approximately reproduce the effective reflection loss model over that range of parameters. Important progress has been made on this task, where we have focused on the special case of an isovelocity sound speed profile. Based in part on physics-based scaling, an algebraic algorithm has been developed with the inputs of frequency, wind speed, and water depth that yields the effective reflection coefficient model that can be used in CASS-GRAB, ASPM, or other simulation models that utilize a surface reflection loss model and that allow range dependence of the surface reflection loss. We will refer to the output of this algorithm as the TOTLOS model in what follows, not the result deduced directly from a particular set of mode amplitudes, as given, for example, in Fig. 6.

Figure 7 shows several reverberation results for the same parameters assumed for Fig. 6. There are two results from transport theory, the solid black line omits effects of forward scattering (i.e., has no surface loss), and the blue solid line is from transport theory where effects of forward scattering are included. In this case, only the trapped modes from the transport theory run were used in obtaining the reverberation. The dashed lines were all obtained with CASS-GRAB runs, and the difference in the early time behavior in this case occurs because the initial ray fan used with CASS-GRAB extended over a wider range of angles than associated with the ± 20 deg of the trapped modes. The red dashed line was obtained using the recent OAML surface loss model (the modified Eckart model). Note the significant increase in reverberation given by the more accurate transport theory than with the modified Eckart surface loss model. The black dashed line is the CASS-GRAB result with no surface loss, and it merges nicely with the corresponding transport theory curve at longer times, as it should. The blue dashed line is the CASS-GRAB result using the TOTLOS surface loss model, and the agreement with transport theory is quite good, keeping in mind that the disagreement at early time is not important because of different modeling assumptions.

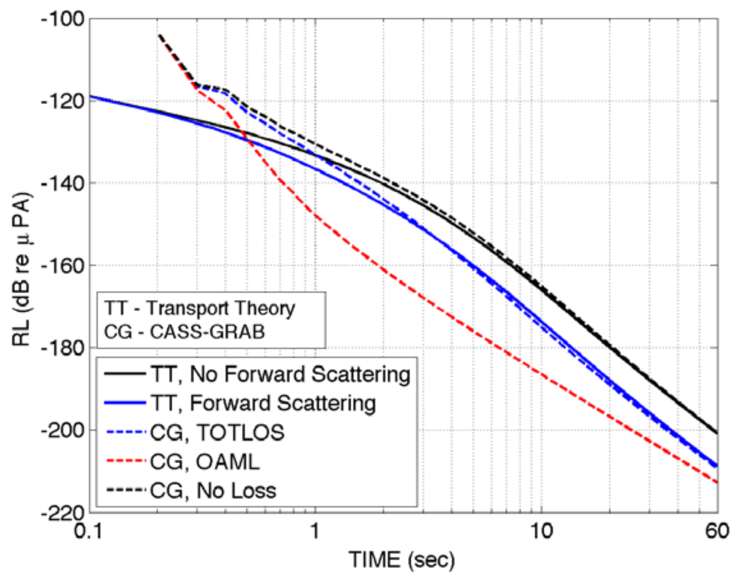

Figure 7. Reverberation results for the same conditions as for Fig. 6.

There is one important caveat that should be mentioned in regard to the results shown in Fig. 7. As mentioned, the transport theory curves were obtained using the 70 trapped modes for this case. The predicted reverberation level will be somewhat higher than the solid blue curve if higher modes than the trapped modes are included. Our mode method and transport theory can account for these higher modes, which correspond to grazing angles above the critical angle. We find that as more modes are included the reverberation level converges to a limiting level. This would be the ideal result for TOTLOS to match, but it appears impractical to extent the effective reflection loss model used in TOTLOS into this region beyond the critical angle, since the number of boundary bounces will become excessive at long range. Thus, our approach in the future will most likely be to bias our TOTLOS model so that its reverberation curves lie slightly above the result from transport theory based only on the trapped modes.

It is instructive to compare results obtained with the present version of TOTLOS with the reverberation difference results from ASIAEX discussed in Section 3. The measured reverberation differences are compared with those obtained with CASS-GRAB using TOTLOS in Figs. 8 and 9 for a frequency of 1 kHz and 2 kHz, respectively. If effects of surface forward scattering were ignored completely, the differences would be 0 dB for all times (not plotted). If surface forward scattering were treated using the coherent reflection loss given by the Modified Eckart model, the predicted reverberation difference is given by the green curves in Figs. 8 and 9, showing greater differences than observed between the two sea state conditions. Finally, if surface forward scattering were treated with the TOTLOS model the result is given by the blue curves, in remarkably good agreement with the data.

A pressing need is to fully document the many results discussed in this report in the literature. The basic equations used in our transport theory are contained in [5], which was written and published in FY10. More detailed treatments of transport theory as applied to surface forward scattering and reverberation are being prepared in ongoing work under support for the FY13-15 time period.

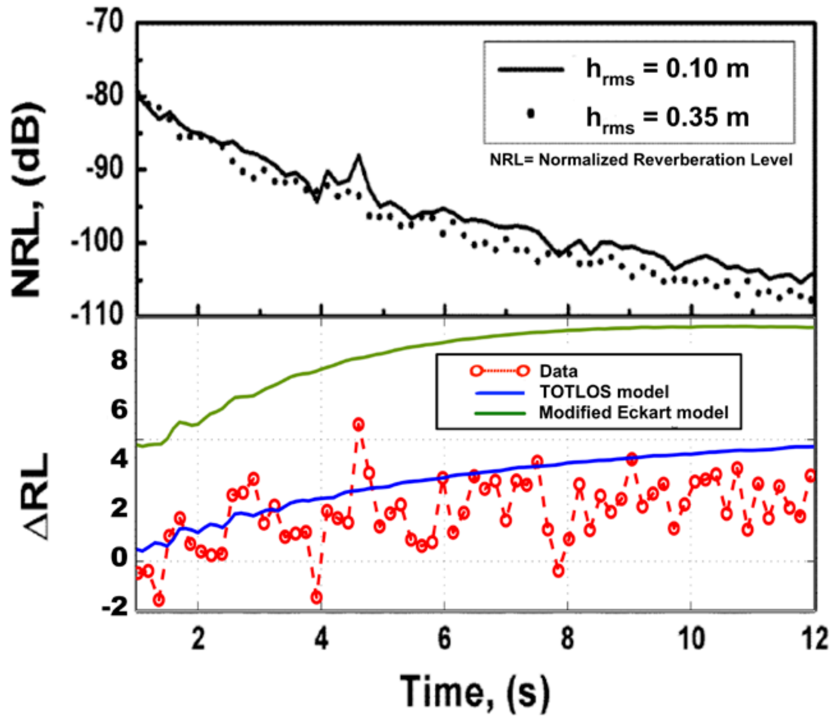

Figure 8. Data/model comparison for 1 kHz reverberation difference between June 3 and 5, 2001. The green curve assumes a coherent loss at the surface, while the blue curve accounts for forward scattering.

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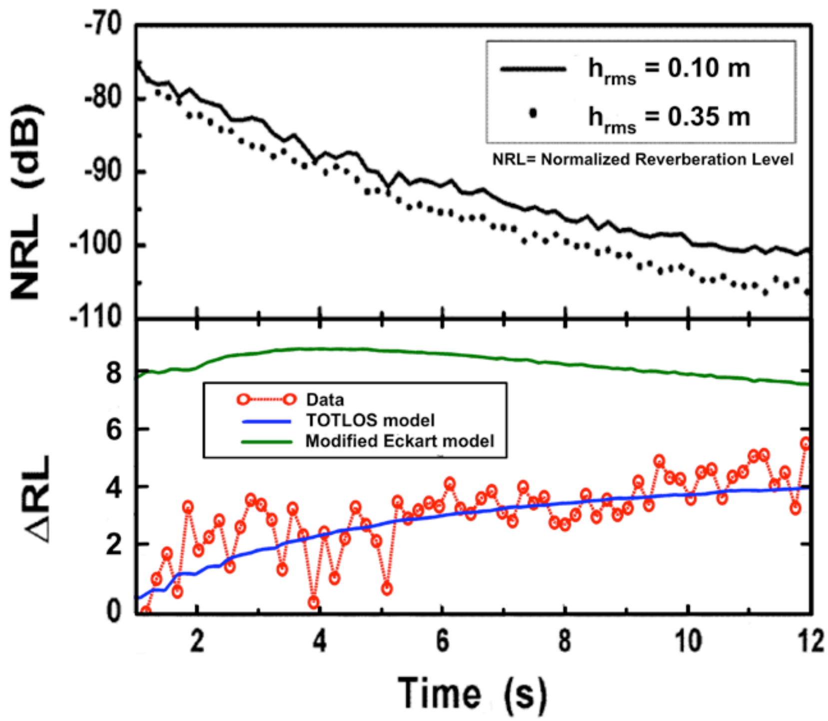

Figure 9. Same as Fig. 8 but for 2 kHz.

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14. ABSTRACT
The main goals proposed for this project were to extend transport theory to range dependent environments and to develop reverberation modeling based on transport theory. The stochastic process emphasized was forward scattering from the sea surface, since it is the most important effect on reverberation modeling that is not being taken into account in reverberation modeling prediction for naval applications. The effect of sea surface forward scattering can affect predicted reverberation levels at mid frequencies by more than 10 dB, and therefore it is one of very few physical effects (if not the only one) not presently being taken into account that can lead to such large reverberation modeling uncertainties. The need to account for surface forward scattering with traditional reverberation modeling approaches readily accessable for naval applications is also being addressed with the development of an effective reflection loss model for the total field, referred to as TOTLOS. The original approach in developing TOTLOS was to base it on the results of Monte Carlo rough surface PE results, but as transport theory became available it became clear that results from it were much more suitable to support TOTLOS development, making it an important secondary goal of the present project.

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